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# FULL-SCALE ALTITUDE ENGINE TEST OF A TURBOFAN EXHAUST-GAS-FORCED MIXER TO REDUCE THRUST SPECIFIC FUEL CONSUMPTION

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16. Abstract

The specific fuel consumption of a low-bypass-ratio, confluent-flow, turbofan engine was measured with and without a mixer installed. Tests were conducted for flight Mach numbers from 0.3 to 1.4 and altitudes from 10 670 to 14 630 meters (35 000 to 48 000 ft) for core-stream-to-fan-stream temperature ratios of 2.0 and 2.5 and mixing-length-to-diameter ratios of 0.95 and 1.74. For these test conditions, the reduction in specific fuel consumption varied from 2.5 percent to 4.0 percent. Pressure loss measurements as well as temperature and pressure surveys at the mixer inlet, the mixer exit, and the nozzle inlet were made.

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# FULL-SCALE ALTITUDE ENGINE TEST OF A TURBOFAN EXHAUST-GAS-FORCED MIXER TO REDUCE THRUST SPECIFIC FUEL CONSUMPTION

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## SUMMARY

An investigation was conducted with a full-scale, low-bypass-ratio, confluent-flow turbofan engine to evaluate an exhaust-gas-forced mixer as a means of reducing engine fuel consumption. Data were obtained at 70- to 100-percent rated fan speed with and without the mixer installed, and the results were compared. Mixer performance was obtained for flight Mach numbers from 0.3 to 1.4 and altitudes from 10 670 to 14 630 meters (35 000 to 48 000 ft). The effect of mixing length on mixer performance was studied by testing two engine tailpipe lengths (length-to-diameter ratios L/D of 0.95 and 1.74). To assess the effect of core-to-fan-stream total temperature ratio, the core flow was reheated, increasing the nominal temperature ratio from 2.0 to 2.5. Pressure and temperature surveys were obtained at the mixer inlet, the mixer exit, and the nozzle inlet.

At a cruise condition (flight Mach number, 0.8; altitude, 10 670 m (35 000 ft)) the mixer reduced the specific fuel consumption by approximately 2.5 percent over the range of fan speed investigated. Increasing the mixing L/D from 0.95 to 1.74 at an altitude of 12 190 meters (40 000 ft) and a Mach number of 1.4 did not change the 2.5-percent reduction in fuel consumption. Also increasing the altitude to 14 530 meters (48 000 ft) did not change the 2.5-percent reduction. When the nominal core-to-fan-stream total temperature ratio was increased from 2.0 to 2.5, the mixer reduced the specific fuel consumption by approximately 4 percent. For all test conditions, the total pressure loss attributed to the mixer was approximately 1 percent.

## INTRODUCTION

The government, the airlines, and the aircraft industry are vitally interested in promoting the efficient use of aviation fuel. The current total U.S. aviation fuel con-

sumption is approximately 20 billion gallons annually. Conservative estimates project this usage to double by the year 2000 (ref. 1). Based on current usage and price, a 1-percent decrease in aircraft fuel consumption is equivalent to an annual fuel expenditure savings of $50 million. An engine component suggested in reference 1 to reduce turbofan fuel consumption is the exhaust gas mixer. The mixer is a convoluted, sheet-metal device that promotes the mixing of the core and fan exhaust streams. This enhanced mixing of the hot and cold streams prior to their discharge through a common nozzle increases propulsive efficiency and thereby decreases engine fuel consumption. The fuel savings potential of exhaust gas mixers had been previously investigated in theory and model tests (refs. 2 to 4). There is a dearth of mixer performance data from full-scale-engine altitude tests.

An investigation was conducted at the NASA Lewis Research Center with a full-scale turbofan engine to determine the effect of an exhaust-gas-forced mixer on engine specific fuel consumption. A confluent-flow turbofan engine was installed in an altitude test facility and was operated over ranges of Mach number, altitude, and fan speed with and without a mixer installed to determine the reduction in engine fuel consumption obtained with the mixer. The effect of mixing length and core-to-fan-stream total temperature ratio on the reduction in mixer fuel consumption was also evaluated. The effect of the mixer installation on the experimentally obtained engine operating parameters is presented. An engine performance computer deck was used to analyze theoretically the effect of the mixer on engine operation. Pressure and temperature surveys were obtained at the mixer inlet, the mixer exit, and the exhaust nozzle inlet.

## APPARATUS

### Engine

The engine used for this investigation was a TF30-P-1 two-spool turbofan engine (fig. 1). The compressors, combustion section, and turbines on this engine are standard components. The three-stage, axial-flow fan is mounted on the same shaft with a six-stage, axial-flow, low-pressure compressor. This assembly is driven by a three-stage, low-pressure turbine. A seven-stage, axial-flow, high-pressure compressor is driven by a single-stage, air-cooled turbine. The compressor system overall pressure ratio is 17, the fan pressure ratio is 2.1, and the fan bypass ratio is 1 at sea-level-static intermediate operating condition. A splitter ring divides the core and fan airflow at the exit of the third-stage rotor. The annular fan duct airflow combines with the turbine flow at the afterburner inlet. The combined flow discharges through a variable-area exhaust nozzle.

Several modifications were made to the engine. At the turbine exit plane, a multiple-ring-injector, gaseous hydrogen burner was installed in an extended core duct section (fig. 1). This burner was used to reheat the turbine discharge flow in order to investigate the effect of increased core-to-fan-stream total temperature ratio. Hydrogen was supplied through three zone-control valves that were manually regulated to obtain the desired temperature rise and to maintain a uniform radial profile. The four-ring hydrogen injector can be seen in figure 2 (center). A screen of sufficient porosity to balance the pressure drop due to the hydrogen injectors in the core stream was installed in the fan duct. A pressure drop balance was needed in the core and fan streams to maintain the heater-equipped engine on the standard engine operating line. Elements of this low-porosity screen are visible through the fan chutes in figure 2.

The afterburner hardware, fuel injection manifolds, and flameholders were removed. The flow mixer (fig. 3) was then installed in a modified diffuser casing of the same internal configuration as the original diffuser.

The standard afterburner tailpipe was replaced with multiple-flanged casing sections and matching liner sections that were removable. In this manner, the tailpipe length-to-diameter ratio L/D could be reduced from the standard value of 1.74 to 0.95. Also, the exit leaves and blowin doors usually mounted on the ejector nozzle were removed.

The standard, integrated, afterburner-fuel-flow exhaust nozzle control was replaced with a single exhaust nozzle area control. The nozzle control could operate in either manual or automatic mode. This control system automatically varied the exhaust nozzle area to maintain a prescribed turbine pressure ratio when the hydrogen burner was used.

## Mixer

The mixer tested has 20 core flow chutes and 20 fan flow chutes and is shown schematically in figure 4. This mixer is classified as a partial mixer, handling the total fan airflow but only part of the core gas flow. The mixer and the tailpipe correspond to an L/D of 0.95 and have an interface area function, as defined by Frost (ref. 4), of approximately 15. A mixer with an interface function over 10 should have a theoretical mixing effectiveness above 80 percent. The mixer is fabricated from nominally 0.122-centimeter-thick (0.048-in.-thick) Hastelloy-X and weighs 25.9 kilograms (57 lb). This research hardware was fabricated for a previous program that had a more severe test environment. A flight-qualified mixer probably would not be constructed of this gage or density of material and thereby would weigh less. The

mixer is shown in figure 3 after approximately 35 hours of testing, half of which were in the more severe environment. The hardware is in good condition. The holes in the chutes were required for other tests and were left unplugged in these tests. The mixer is shown installed in the engine in figure 2.

## Engine Installation

The installation of the engine in the altitude chamber, a conventional direct-connect type, is shown in figure 5. At the right is the forward bulkhead, which separates the 5.5-meter-diameter (18-ft-diam) inlet plenum from the 7.3-meter-diameter (24-ft-diam) test chamber. The required pressure and temperature air flows from the plenum at the right, through the bellmouth, and into the engine inlet duct (fig. 1). A conical screen is attached to the bellmouth to prevent foreign object ingestion. A labyrinth seal, shown schematically in figure 1, is used to isolate the inlet ducting and thus allow free movement of the engine.

The engine, shown with the 0.95 L/D tailpipe (fig. 5), was hung from an overhead mounting structure on the thrust bed. The thrust bed is suspended by four multiflexured vertical rods attached at their upper ends to the chamber. The bed alinement with the airflow direction is maintained by two multiflexured horizontal rods located fore and aft on the far side of the bed. The thrust bed is restrained from free movement by a dual load-cell system that allows the bed to be preloaded.

Engine exhaust gases are captured by a movable water-cooled collector extending from the rear bulkhead at the left. The collector minimizes exhaust gas recirculation in the test chamber. It was moved to maintain the same position relative to the engine nozzle when the tailpipe length was changed.

## Instrumentation

The instrumentation station identification and probe locations are shown in figure 1. Instrumentation was identical for tests with and without the mixer installed. When the mixer was installed, the rakes at the mixer outlet (station 8) were located on the mixer chute radial centerlines. The rake at $252^{\circ}$ was on the centerline of a core chute, and the rake at $315^{\circ}$ was alined with the centerline of a fan chute. At the nozzle inlet (station 9), the rake at $207^{\circ}$ was located on a fan chute centerline and the rake at $270^{\circ}$ was located on a core chute centerline. The cross-duct total pressure rake at station 9 is almost alined with the interface between the core and fan chutes. The rake installation at stations 8 and 9 is shown in figure 2.

Pressures were recorded on 13 Scanivalves (24 ports each) that were operated by the facility computer. The differential Scanivalve transducers were calibrated while in use and therefore had an estimated system accuracy of ±0.26 percent full scale. The individual differential transducer accuracy was ±0.60 percent full scale.

All thermocouples were Chromel-Alumel type and were referenced to a 339 K (610° R) oven. Their estimated accuracy was +1.1 K (±2.0° R).

The engine thrust and the thrust-bed preload forces were measured separately with 44 500-newton (10 000-lb) strain-gage load cells. The load cells were independently calibrated and mounted beneath the thrust bed. The thrust measuring system accuracy was ±36 newtons (±8 lb).

The engine fuel flow was measured by two turbine flowmeters mounted in series. The flowmeters were individually calibrated and were accurate to ±0.56 percent full scale. The fuel temperature was measured at the upstream flowmeter inlet.

## PROCEDURE

To conduct a valid performance test of the turbofan exhaust gas mixer in a ground facility, the correct flight environment should be simulated. Also, to improve the accuracy of the performance comparison, it was desired to obtain performance data with and without the mixer installed during one test period. To simulate a standard-day cruise condition of Mach 0.8 at 10 670-meter (35 000-ft) altitude requires an inlet temperature of 247 K (444° R). When testing at this subfreezing temperature, the facility inlet piping must be conditioned before the data run by a long period of drying and cooling of the inlet system. This required conditioning time made it impossible to have standard-day cruise conditions and collect data with and without the mixer installed in the allocated time period. Therefore, data were obtained for Mach 0.8 cruise flight conditions at the inlet air temperature of 247 K (444° R) only with the mixer installed. All comparison tests in which data were obtained with and without the mixer were conducted with inlet air at 289 K (520° R). The inlet temperature of 289 K (520° R) represents standard-day conditions for the data taken at Mach 1.4 at altitude. The test conditions are summarized in table I.

For the comparison tests, data were obtained at the desired altitudes, Mach numbers, and fan speeds with the mixer installed. The test was halted and the mixer was removed. The test was resumed, and data were obtained without the mixer at the same operating conditions and fan speeds. In this manner, comparison data were obtained with the same data acquisition system setup and instrumentation calibrations. For further data verification, the thrust bed was calibrated at altitude before and after each test.

The low-compressor (seventh stage) and the high-compressor (12th stage) bleeds were closed for all operating points considered herein.

The variable-area exhaust nozzle was "closed" (rated area) for all data taken at the normal core-to-fan-stream total temperature ratio of 2.0. (The actual temperature ratio varied from 1.92 to 2.19.) When this ratio was increased to 2.5 (actually, 2.44 to 2.63) by using the hydrogen heater, the nozzle, which was controlled by the turbine pressure ratio, was allowed to automatically open in order to maintain the standard engine operating point. When the hydrogen heater was operated, the maximum nozzle area was 12 percent greater than the rated area.

## RESULTS AND DISCUSSION

### Engine Operating Conditions

Comparative tests with and without the mixer installed were conducted at an inlet temperature of 289 K (520° R) rather than the lower inlet temperature corresponding to standard day, Mach 0.8, cruise conditions. As explained in the section PROCEDURE, this was necessary because the time-consuming startup procedure required with refrigerated air precluded completing a comparative test in a single run. Therefore, it should be verified that the engine parameters affecting mixer performance were similar even though the inlet temperature for the comparative tests at Mach 0.8 was 289 K (520° R) instead of the standard-day value of 247 K (444° R). In the following figures, several engine parameters are presented for comparison at the two inlet temperatures for 10 670-meter (35 000-ft) altitude and Mach 0.8.

Also of concern in a comparative test is the effect of the mixer installation on the engine operating point. If the operating point changed substantially when the mixer was installed, it would be difficult to assess the engine performance change due to mixing alone. Several engine operating parameters are presented over a range of Mach number and altitude with and without the mixer installed. From these data, the effect of the mixer installation on operating point can be observed.

Engine speed match. - In figure 6, the fan-to-core speed match is shown. The solid line represents the speed match for the engine operating at standard-day cruise conditions, 10 670 meters (35 000 ft) at Mach 0.8 with the mixer installed. This is compared with the 289 K (520° R) inlet temperature data with the mixer (solid diamond symbols) for the same altitude and Mach number. The data for the two inlet temperatures, 247 K (444° R) and 289 K (520° R), compare favorably. Therefore, the speed match with the mixer installed is essentially the same for the two inlet temperatures.

For the comparative tests with and without the mixer, a majority of the data show

a change in the speed match. At a given core speed, the installation of the mixer decreases the fan speed. The maximum decrease in fan speed, approximately 1 percent, occurs at 10 670-meter (35 000-ft) altitude at Mach 0.8. A decrease in the fan speed relative to the core speed can probably be expected when the mixer is installed. The mixer is classified as a partial mixer, handling the total fan flow but only part of the core flow. Therefore, the mixer would backpressure the fan duct to a greater degree, causing a decrease in the fan speed relative to the core speed.

Bypass ratio. - The variation of engine bypass ratio with fan speed is shown in figure 7. There is good agreement between the standard-day data at Mach 0.8 and the 289 K (520° R) inlet temperature data at the same altitude and Mach number.

For the comparative test when the mixer is installed, the bypass ratio decreases at a given fan speed. This observation agrees with the previous statement that the mixer backpressures the fan duct to a greater degree than the core duct, resulting in a redistribution of airflow from the fan duct to the core duct.

Total engine airflow. - The engine airflow - fan speed characteristic is shown in figure 8. There is good agreement between the 247 K (444° R) inlet temperature data and the 289 K (520° R) inlet temperature data for the Mach 0.8 cruise condition.

In comparing the airflow data with and without the mixer at a given fan speed, there does not appear to be a consistent shift caused by the mixer installation. But, it is recalled from the speed match curve (fig. 6) that, for a given core speed, the fan operates at a lower speed with the mixer installed. Therefore, at a given core speed the total engine airflow is decreased when the mixer is installed.

Engine pressure ratio. - The engine pressure ratio (EPR) variation with fan speed is shown in figure 9. All available data are not plotted in the figure for reasons of clarity. The data set shown, for Mach 0.8 and 289 K (520° R) inlet temperature, corresponds to the maximum shift in the speed match (fig. 6). Data for Mach 1.4 and a core-to-fan-stream temperature ratio of 2.0 were almost identical to the Mach 0.8 data and therefore were not plotted. The 247 K (444° R) data and the 289 K (520° R) data at Mach 0.8 and 10 670-meter (35 000-ft) altitude with the mixer show close agreement. Therefore, the inlet temperature change had no measurable effect on the EPR.

For the comparative test, at a given fan speed, the EPR is higher with the mixer installed. If EPR is used as an indication of engine operating point, these data show that the fan speed could be decreased to lower the EPR with the mixer to match the EPR without the mixer. The operating point based on EPR would then be the same with or without the mixer, but the fan speed would be lower with the mixer. Experimental data showed the engine fuel flow to be the same with or without the mixer at a given fan speed. So if the fan speed with the mixer is lowered to match EPR values, the fuel consumption would be less for the engine with the mixer, thus showing that the mixer conserves fuel while maintaining a given EPR.

Core-to-fan-stream total temperature ratio. - The variation of the core-to-fan-stream total temperature ratio with fan speed with the mixer installed is shown in figure 10. The temperature ratio variation at Mach 0.8 and 289 K (520° R) inlet temperature agrees with the standard-day cruise condition. Over the range of fan speeds considered here, the temperature ratio varied from 1.92 to 2.19. Considering the range in speed, this is a relatively small change in temperature ratio.

When the core-duct hydrogen heater is operated, the temperature ratio obviously increases. With the heater in operation, the temperature ratio varied from 2.44 to 2.63 over the range of fan speed. This is not an appreciable change in temperature ratio considering the large range in fan speed.

Summary of engine operating data. - The engine operating data obtained at an inlet temperature of 289 K (520° R) are almost identical to those data obtained at the standard-day temperature, 247 K (444° R), for the Mach 0.8 cruise condition. Therefore, the conclusions obtained from the comparative tests with and without the mixer at 289 K (520° R) should also pertain to the standard-day subsonic cruise condition.

The effect of the mixer installation on engine operation can be assessed by analyzing the engine data experimentally obtained with and without the mixer. The installation of the mixer decreased the fan speed and the total engine airflow at a given core speed. At a given fan speed, the EPR increased and the bypass ratio decreased with the mixer. Analysis of these engine operating data shows the effects produced by the mixer. But this analysis of experimental data does not produce a clear understanding of mixer-engine operating interaction.

To gain further insight into the effect of the mixer on the engine operating point, a theoretical investigation was also made. A TF30 engine performance computer deck was used to analyze the engine operation with and without the mixer installed. The results of this theoretical analysis agreed with the trends shown by the experimental data in figures 6 to 10. For example, the computer deck predicted that, for a given fan speed with and without the mixer, the total airflow would be the same and that the engine pressure ratio would increase when the mixer was installed. Performance deck calculations of core-to-fan-stream total temperature ratios and thrust specific fuel consumption (TSFC) agreed very well with experimental values. The TSFC variation as predicted by the computer deck is presented in figure 11. The "no mixer" curve was calculated with no additional tailpipe total pressure drop. This case represents the TF30 with the afterburner hardware, flameholders, and fuel manifolds removed.

The two cases with the mixer installed were calculated with a 1-percent total pressure drop. This pressure drop was an experimentally obtained average value attributed to the mixer. Also, the fan-to-core flow area distribution corresponding to the mixer exit was assigned in both cases. In the first case with the mixer installed, no mixing was permitted. This case was calculated to separate the effect of the

physical presence of the mixer from the effect of the mixing process on the engine fuel consumption. This calculation produced the upper curve shown in figure 11. At the fan speed corresponding to minimum TSFC, it appears that a 0.5-percent penalty in TSFC was incurred solely by the physical presence of the mixer. The 1-percent pressure drop is the major contributor to the rise in TSFC above the values shown for the no-mixer case. In the second case with the mixer installed, complete mixing was specified. This calculation resulted in the lower curve in figure 11. Comparing this curve and the no-mixer curve shows that a TSFC improvement of 4.3 percent is possible, assuming complete mixing.

The experimentally obtained values of TSFC with and without the mixer are also presented in figure 11. The trend of the data agrees with the predicted curves, but the absolute values of TSFC differ slightly, particularly in the lower range of fan speed.

## Mixer Performance

Mixer performance is evaluated in terms of TSFC improvement and total-pressure-loss penalty with fan speed. The effects of flight Mach number, flight altitude, mixing length, and core-to-fan-stream total temperature ratio on mixer performance are considered.

The ratio of TSFC without the mixer to that with the mixer is presented in figure 12(a) with fan speed for several subsonic flight Mach numbers at an altitude of 10 670 meters (35 000 ft). The data for Mach 0.8 appear to be fairly constant over the range of fan speed and show a reduction in TSFC of about 2.5 percent. The fact that the reduction is fairly constant and does not decrease at the lower values of fan speed may be attributed to the fairly constant core-to-fan-stream total temperature ratio over this range of fan speeds (fig. 10). Because the reduction in TSFC with the mixer strongly depends on core-to-fan-stream temperature ratio, which is shown later, it is felt that this engine operating characteristic contributes to the constant reduction in TSFC with engine speed. At Mach 0.8, the nozzle pressure ratio was 2.3 at 82-percent rated fan speed.

From the limited data recorded at the lower Mach numbers at 82-percent rated fan speed, a trend with Mach number was not evident. If anything, it appeared that the TSFC reduction was about the same as that for Mach 0.8. At Mach 0.3 and 0.5, the nozzle pressure ratios were 1.7 and 1.8, respectively.

The total pressure loss attributed to the mixer at these subsonic Mach numbers is presented in figure 12(b). For Mach 0.8, the mixer total pressure loss is 0.9 to 1.2 percent.

In figure 13, the mixer performance is presented for two mixing lengths at

Mach 1.4. Also, data are included at two flight altitudes at the longer mixing length. For the 0.95 L/D data, the TSFC reduction at the higher fan speeds was about 2.5 percent. As the mixing length was increased to an L/D of 1.74, the reduction did not change. There was no further reduction with mixing length, apparently because the free mixing did not increase substantially with the added mixing length. Also, free mixing may be a small contribution to the total mixing as compared with forced mixing. The increase in mixing length may effect only a small change in the free mixing, which is a minor contribution to the total mixing and therefore the effect is not measurable in the TSFC reduction. Temperature survey data presented later show that very little free mixing occurs as compared with that obtained with the forced mixer.

The limited data recorded at the higher altitude, 14 630 meters (48 000 ft), showed no further TSFC reduction above 2.5 percent with increased altitude. If the data of figures 12(a) and 13(a) are considered together, it appears that the TSFC reduction of 2.5 percent holds over a wide range of flight conditions. This reduction is the same for the subsonic Mach numbers at 10 670 meters (35 000 ft) and for the Mach 1.4 condition at 12 190 and 14 630 meters (40 000 and 48 000 ft). The maximum nozzle pressure ratio was 6.0 for the Mach 1.4 flight conditions.

The total pressure loss attributed to the flow mixer at Mach 1.4 is presented in figure 13(b). The mixer pressure loss is 0.8 to 1.1 percent. The pressure loss appears to be the same for the two mixing lengths. This is expected because the mixer loss is the difference between the tailpipe pressure loss with and without the mixer and therefore should be independent of mixing length. The mixer pressure loss did not appear to change as the flight altitude was changed from 12 190 meters (40 000 ft) to 14 630 meters (48 000 ft).

The effect of the core-to-fan-stream total temperature ratio on mixer performance is considered in figure 14. At the higher fan speeds the mixer reduced the engine TSFC by about 2.5 percent for a temperature ratio of 2.0 (fig. 14(a)). When the temperature ratio was increased to 2.5, the TSFC reduction increased to approximately 4 percent. It appears that the reduction increases as the total temperature or energy difference between the core and the fan stream increases. This trend has been observed theoretically and in model tests reported in references 2 and 4.

The mixer total pressure loss at two core-to-fan-stream total temperature ratios is shown in figure 14(b). The pressure drop attributed to the mixer is 0.8 to 1.3 percent. The change in temperature ratio from 2.0 to 2.5 had no effect on the mixer pressure drop.

## Pressure and Temperature Survey Data

Details of the gas flow through the mixer and the downstream mixing chamber are observed from the total pressure and temperature rake data recorded at the mixer inlet, the mixer exit, and the exhaust nozzle inlet. Rake data were recorded for a mixing length L/D of 0.95. Cruise conditions, Mach 0.8 at 10 670-meter (35 000-ft) altitude, at 82-percent fan speed were chosen as typical of the mixer operating environment.

Pressure and temperature profiles at the mixer inlet (station 7.5) are presented in figure 15 without and with the mixer installed. The profiles are plotted against distance as measured radially inward from the outer fan duct wall. The total pressure appears to be fairly constant across the fan and core ducts. Thus, the core-to-fan-stream total pressure ratio is approximately 1. The pressure in the fan duct is slightly higher with the mixer installed. The core pressure level is the same with or without the mixer. The total temperature profiles show an approximate ratio of 2 between the core and fan stream temperatures. Comparing figures 15(a) and (b) shows that the conditions at station 7.5 are similar without or with the mixer.

The survey data at the mixer exit plane (station 8) are presented in figure 16 without and with the mixer installed. The total pressure profile is relatively flat in both cases. Without the mixer installed, the two rakes at station 8 display similar temperature profiles (fig. 16(a)). The profile is relatively low at the outer wall (fan flow), increases through a free mixing zone, and finally reaches the higher core flow value. When the mixer is installed, the temperature profiles for the two rakes diverge (fig. 16(b)). The rake at $252^{\circ}$ is in line with a core chute centerline, and the rake at $315^{\circ}$ is in line with a fan chute centerline. When figures 16(a) and (b) are compared, the forced mixing of the gas streams by the mixer is obvious. The temperature profile at the core chute exit ($252^{\circ}$) shows the transport of the hot core gases to the region near the outer wall. The penetration of the cool fan air toward the engine centerline is reflected by the temperature profile at $315^{\circ}$.

Survey data at the nozzle inlet plane (station 9) are presented in figure 17 without and with the mixer. Station 9 is near the downstream end of the mixing chamber. The total pressure surveys without the mixer installed show a slight depression in the profile. This pressure defect is probably the loss due to the wake of the splitter ring. The expanded scale of the station 9 pressure data should be noted. The pressure profile with the mixer installed is fairly flat. Without the mixer, the temperature profile at station 9 shows very little free mixing at about 12 centimeters (4.7 in.) from the outer wall when compared with the temperature profile at station 8. The effect of forced mixing produced by the mixer is shown by the temperature profiles in figure 17(b). The profiles show a marked increase in temperature near the outer wall,

reflecting the transport of hot core gas into this region by the mixer core chutes. Also, the fan chutes direct the cool fan flow inward toward the core region. This forced mixing and subsequent transfer of thermal energy account for the movement of the cool gas/hot gas interface to the right, or toward the engine centerline. The temperature profiles at $207^{\circ}$ (fan duct centerline) and $270^{\circ}$ (core duct centerline) are similar. Because these two temperature profiles are similar, reflecting circumferential thermal uniformity, it would appear that a significant amount of forced mixing has occurred. This thermal mixing occurring at a low level of total pressure loss is responsible for the reduction in specific fuel consumption.

## SUMMARY OF RESULTS

An altitude performance test was conducted with a low-bypass-ratio, confluent-flow, turbofan engine with and without an exhaust-gas-forced mixer installed. The following results were obtained from this investigation:

1. The mixer reduced the thrust specific fuel consumption by 2.5 percent over the range of engine operation from subsonic flight Mach numbers at 10 670-meter (35 000-ft) altitude to Mach 1.4 at 14 630-meter (48 000-ft) altitude. For these test conditions, the nozzle pressure ratio varied from 1.7 to 6.0.

2. As the core-to-fan-stream total temperature ratio was increased from 2.0 to 2.5, the reduction in specific fuel consumption increased from 2.5 percent to 4.0 percent.

3. When the mixing-length-to-diameter ratio downstream of the mixer was changed from 0.95 to 1.74, the reduction in specific fuel consumption remained unchanged at 2.5 percent.

4. For all the conditions tested, the measured total pressure loss attributed to the mixer was approximately 0.8 to 1.2 percent.

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## APPENDIX - SYMBOLS

| | |
|---|---|
| D | tailpipe diameter, m; ft |
| EPR | engine pressure ratio |
| L | tailpipe length, m; ft |
| N1 | fan rotor speed, rpm |
| N2 | core rotor speed, rpm |
| PLTPX | pressure loss in tailpipe, percent |
| TSFC | thrust specific fuel consumption, kg/(hr)(N); lb/(hr)(lb) |
| WAC | core gas flow, kg/sec; lb/sec |
| WAF | fan airflow, kg/sec; lb/sec |
| WA1 | total airflow, kg/sec; lb/sec |
| $\delta$ | ratio of total pressure to standard sea-level static pressure |
| $\theta$ | ratio of total temperature to standard sea-level static temperature |

Subscripts:

| | |
|---|---|
| mixer | exhaust gas mixer installed |
| 2 | fan inlet |
| 7.5 | mixer inlet |
| 8 | mixer outlet |
| 9 | nozzle inlet |

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TABLE I. - SUMMARY OF TEST CONDITIONS

| Simulated flight Mach number | Simulated altitude | | Engine inlet temperature | | Mixing-length-to-diameter ratio | Core-to-fan-stream temperature ratio |
|---|---|---|---|---|---|---|
| | m | ft | K | $^{o}R$ | | |
| 0.3 | 10 670 | 35 000 | 289 | 520 | 0.95 | 2.0 |
| .5 | ↓ | ↓ | 289 | 520 | ↓ | ↓ |
| .8 | | | 289 | 520 | | |
| .8 | | | 247 | 444 | | |
| 1.4 | 12 190 | 40 000 | 289 | 520 | | 2.5 |
| | 12 190 | 40 000 | ↓ | ↓ | ↓ | 2.0 |
| | 12 190 | 40 000 | | | 1.74 | ↓ |
| | 14 630 | 48 000 | | | .95 | |
| | 14 630 | 48 000 | | | 1.74 | |

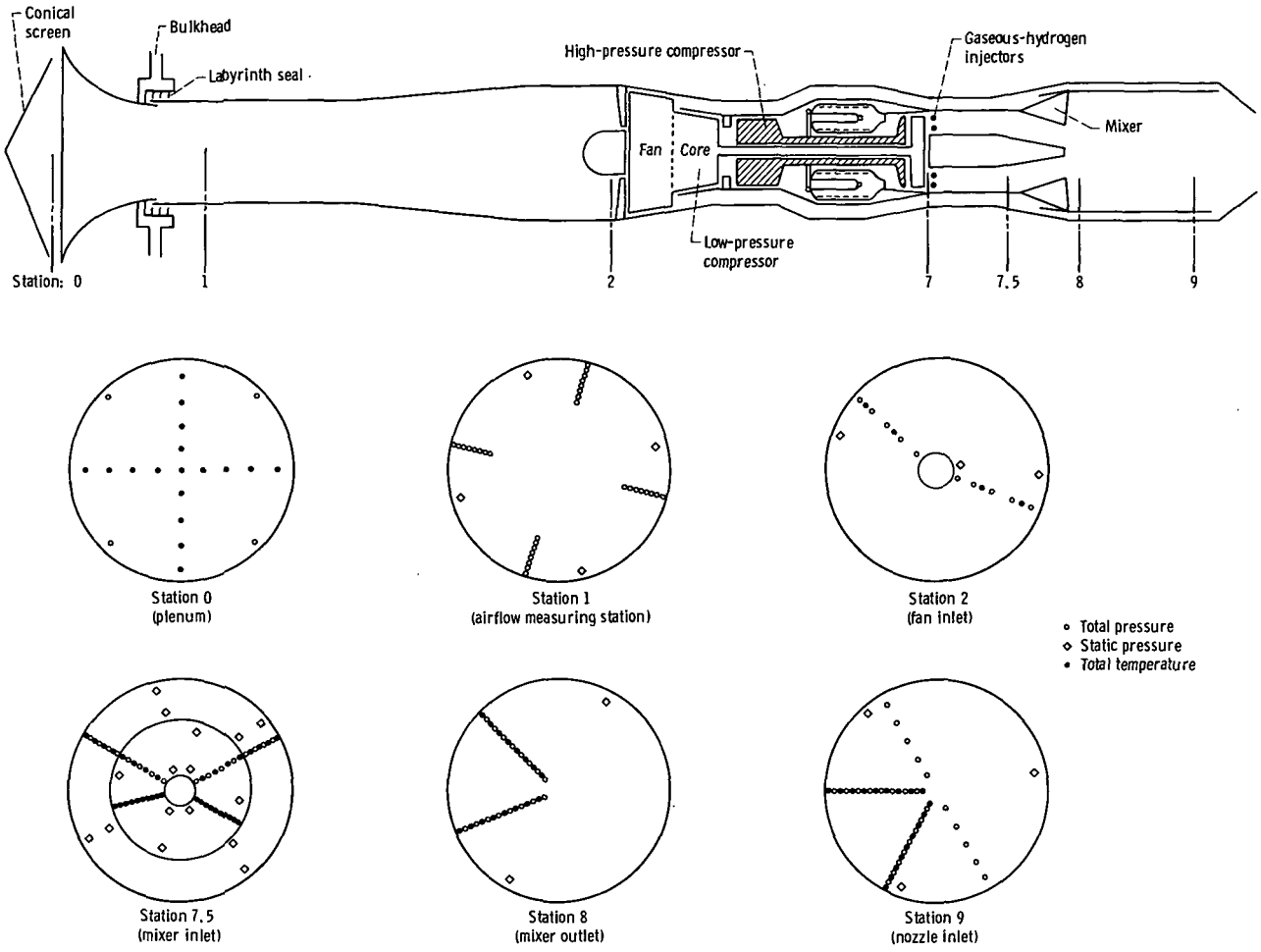



Figure 1. - Instrumentation layout (stations viewed looking upstream).

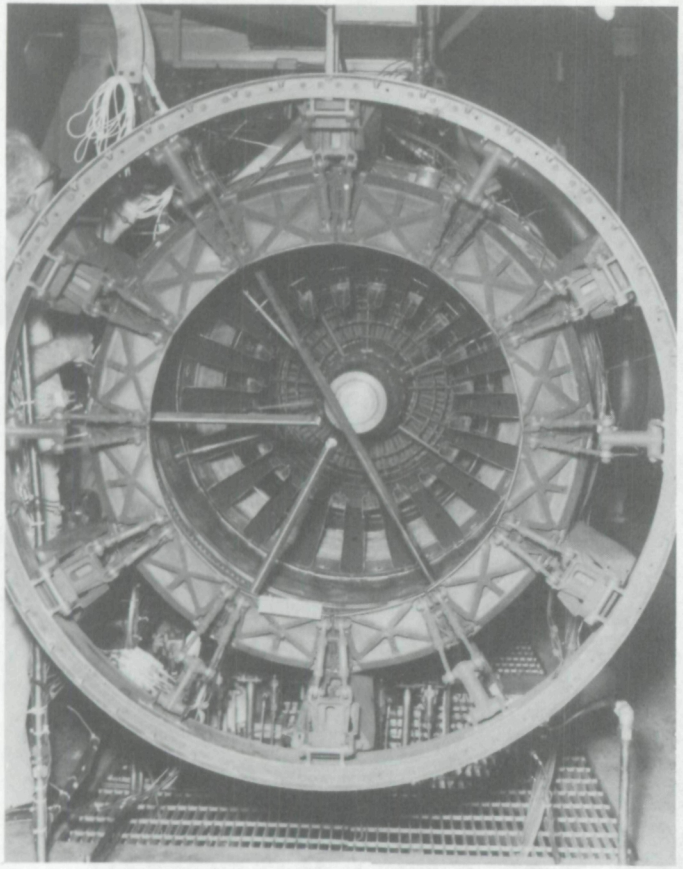


Figure 2. - Exhaust gas mixer and instrumentation installation.

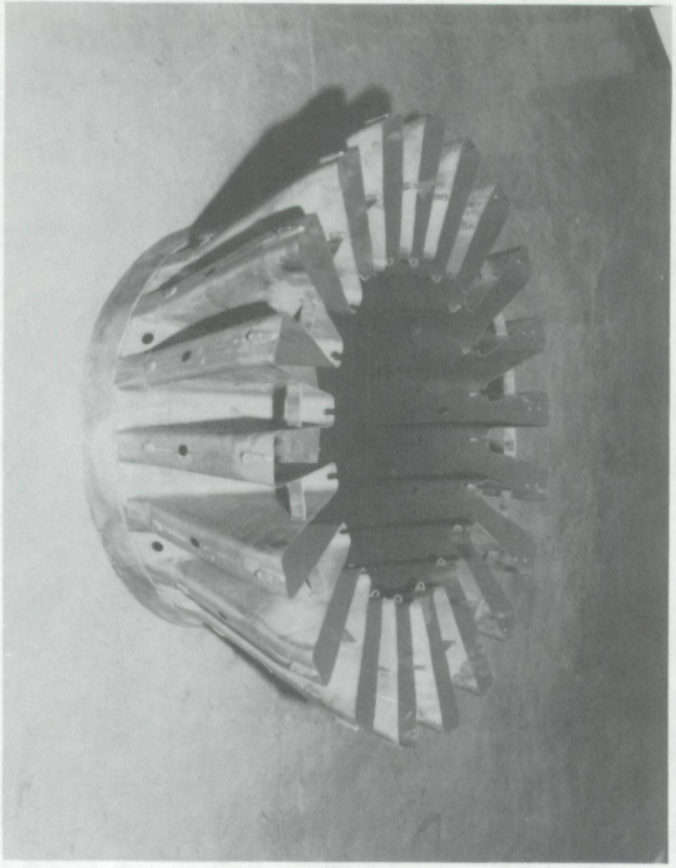


Figure 3. - Exhaust gas mixer.

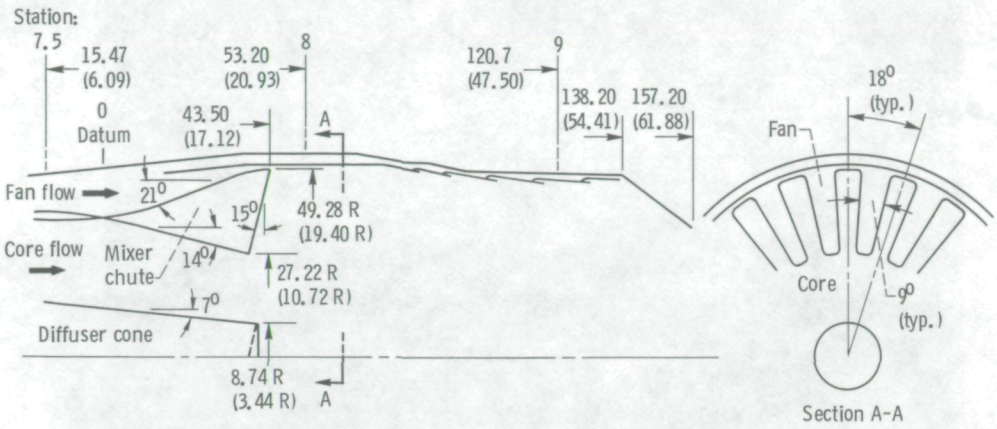



Figure 4. - Cross-sectional schematic of turbofan exhaust gas mixer. Mixing-length-to-diameter ratio L/D of 0.95 shown. Mixing L/D of 1.74 achieved by adding 78.8-cm-long (31.0-in.-long) section downstream of station 8. (Dimensions are in cm (in.).)

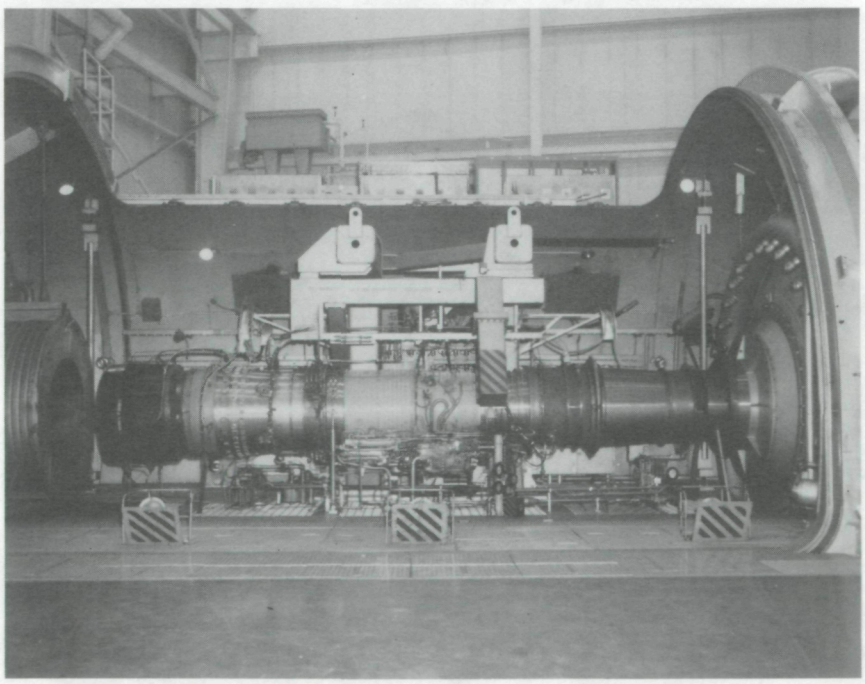


Figure 5. - Turbofan engine installation in altitude test chamber.

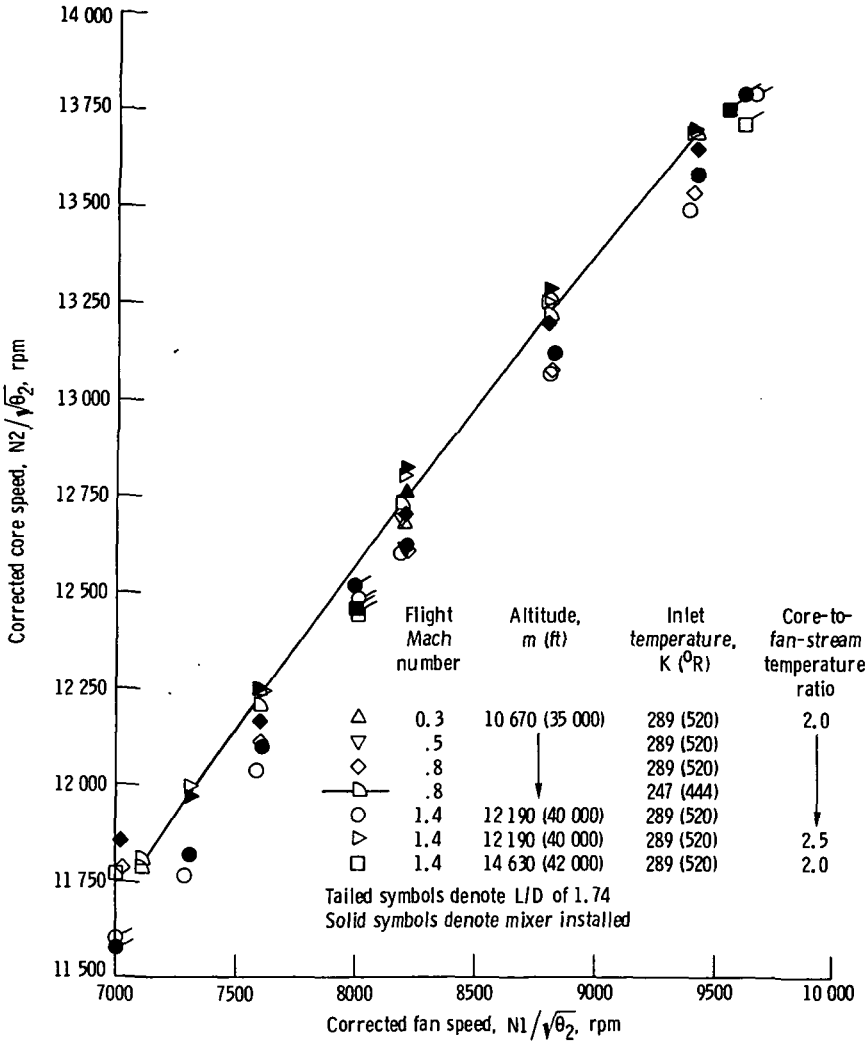



Figure 6. - Engine speed match. Mixing-length-to-diameter ratio, L/D, 0.95.

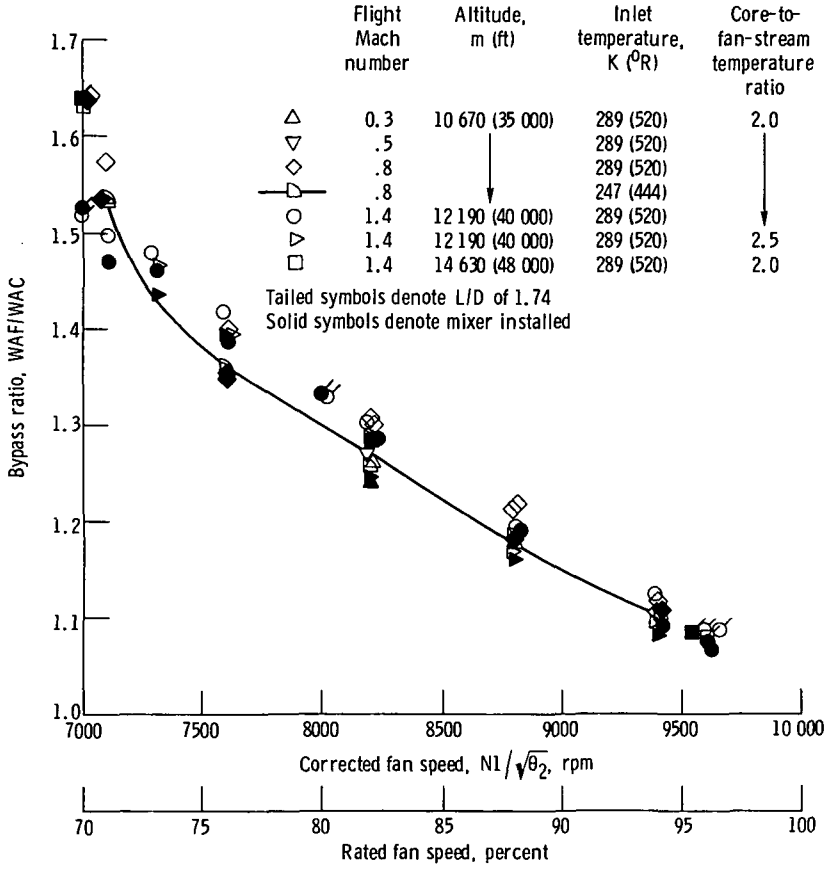



Figure 7. - Engine bypass-ratio match. Mixing-length-to-diameter ratio, L/D, 0.95.

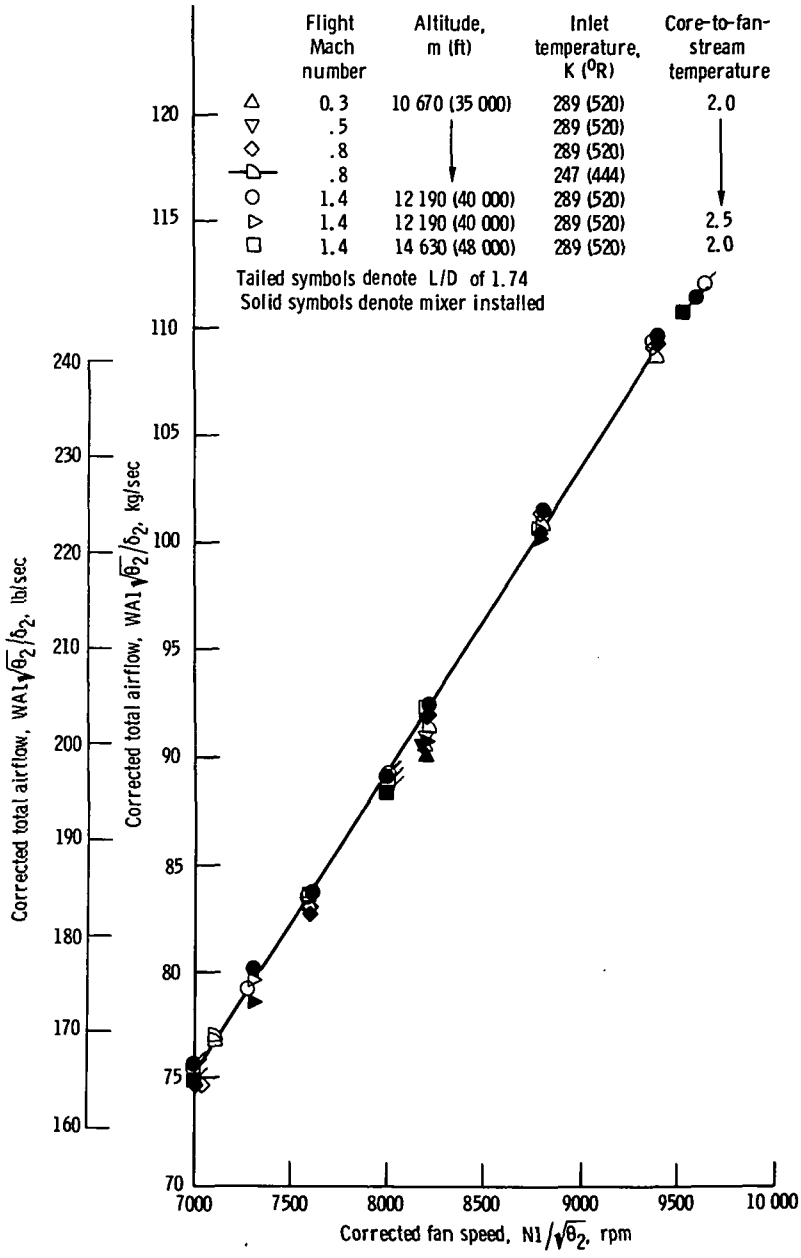



Figure 8. - Engine airflow-speed match. Mixing-length-to-diameter ratio, L/D, 0.95.

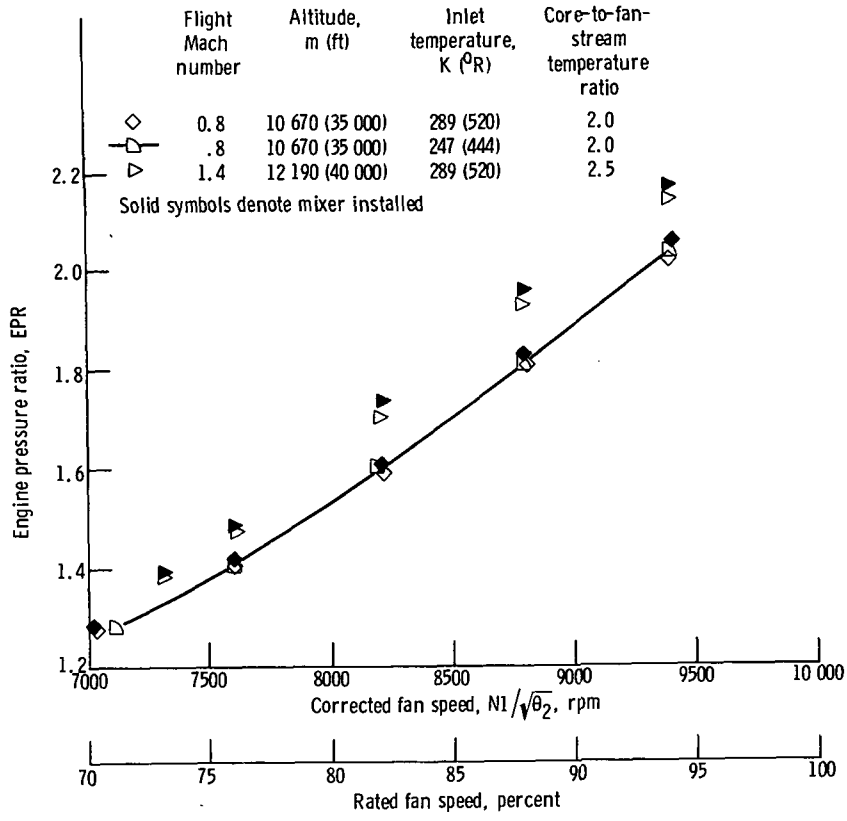



Figure 9. - Engine pressure ratio - speed match.

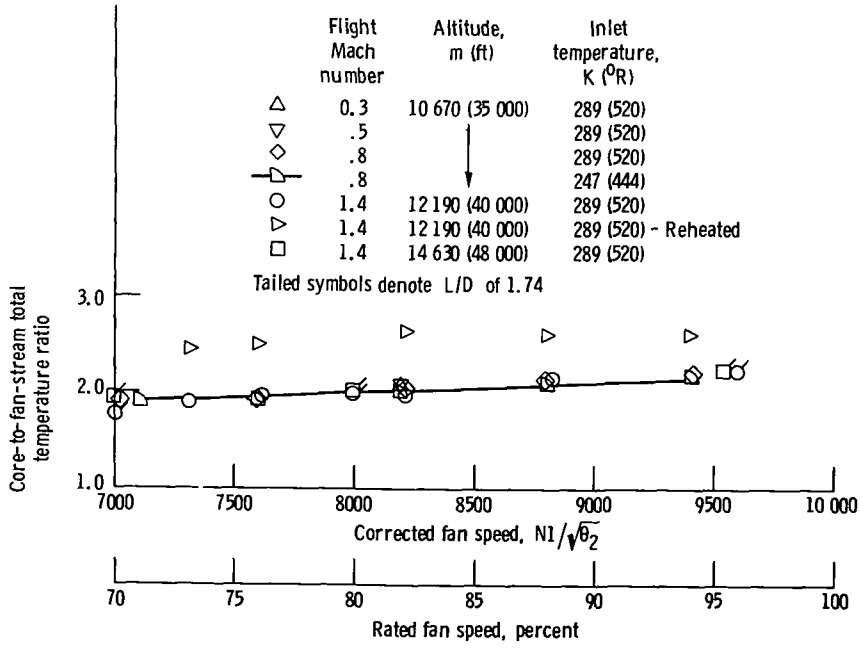



Figure 10. - Core-to-fan-stream temperature ratio variation with mixer installed. Mixing-length-to-diameter ratio, L/D, 0.95.

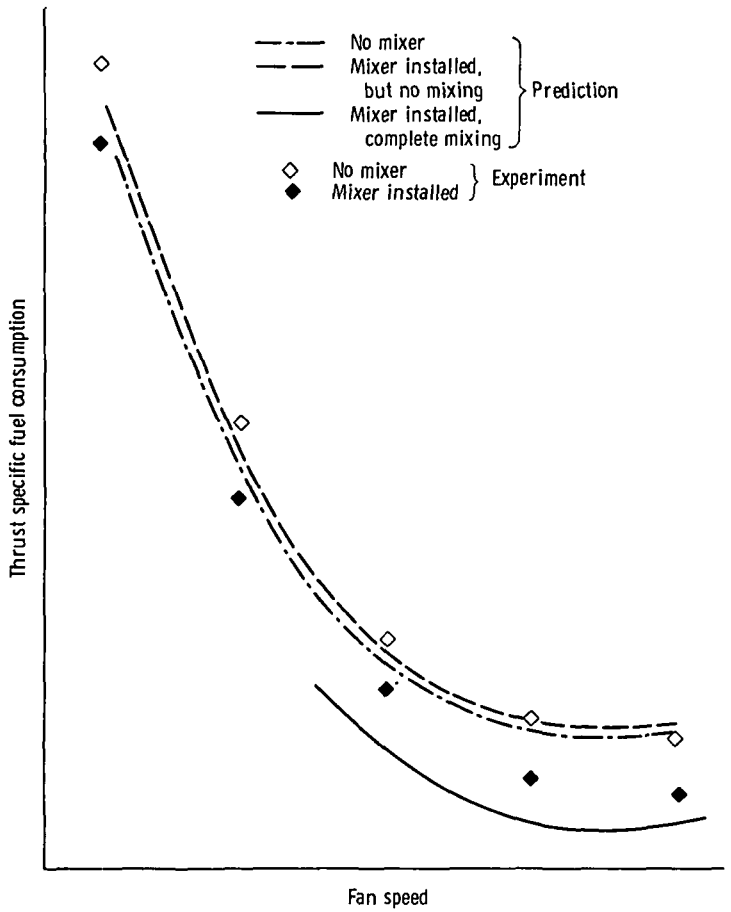



Figure 11. - Predicted and experimental fuel consumption at subsonic cruise conditions.

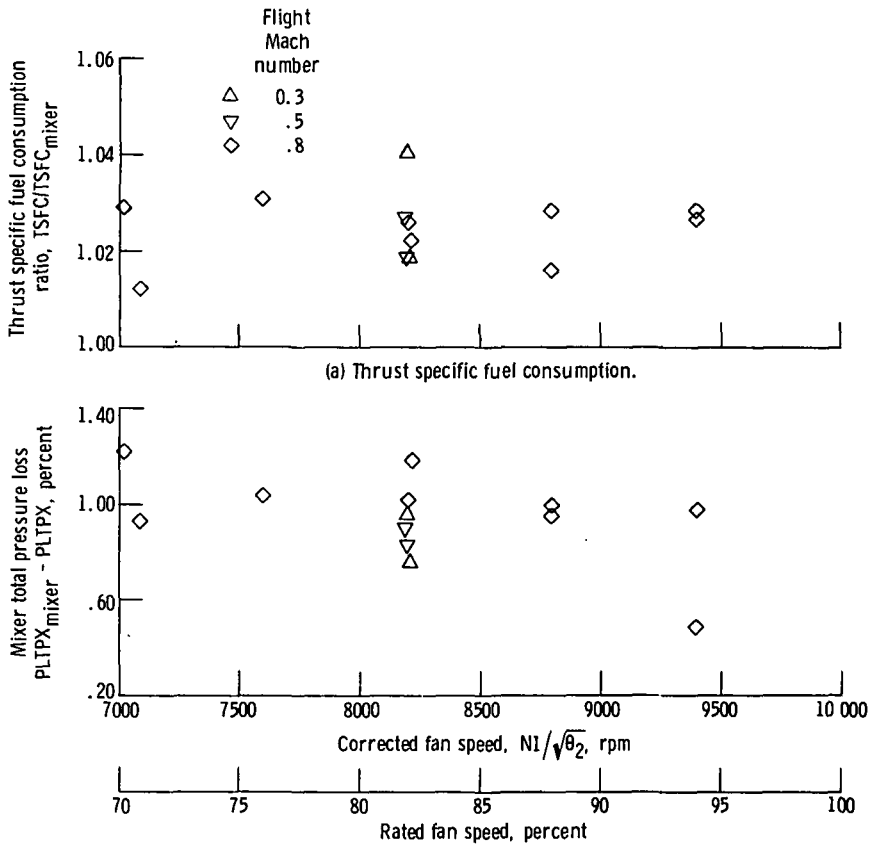
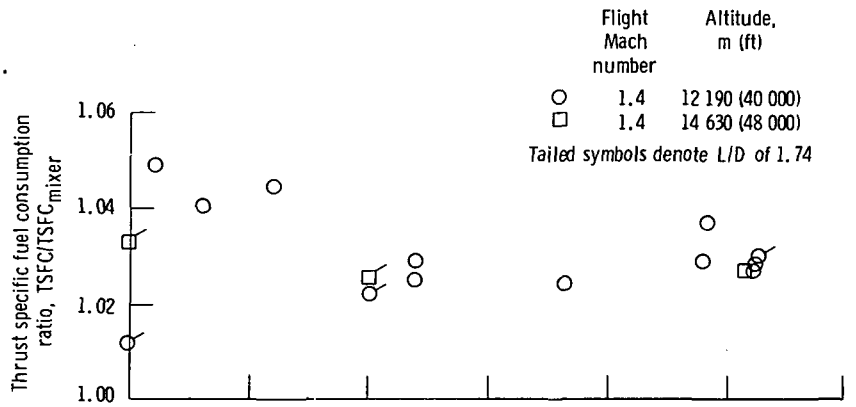
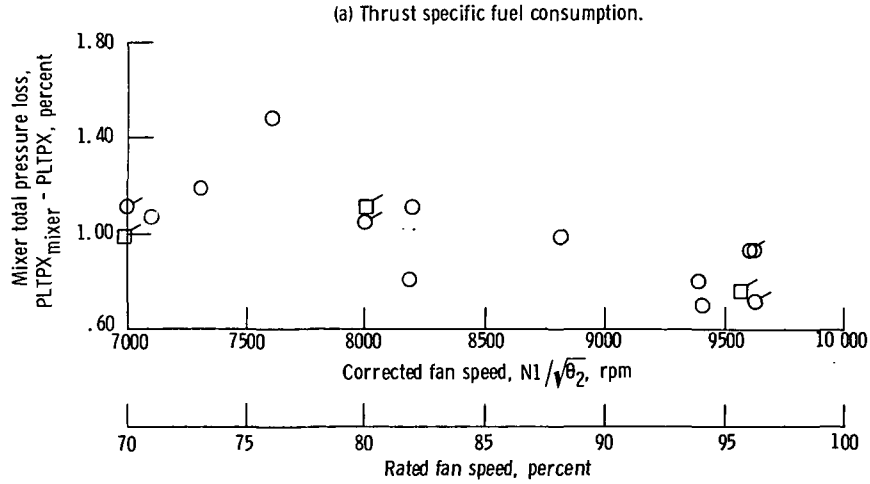



Figure 12. - Mixer performance at three subsonic Mach numbers. Altitude, 10 670 meters (35 000 ft); mixing-length-to-diameter ratio, L/D, 0.95.




(a) Thrust specific fuel consumption.




(b) Mixer total pressure loss.

Figure 13. - Mixer performance for two mixing lengths. Mixing-length-to-diameter ratio, L/D, 0.95.

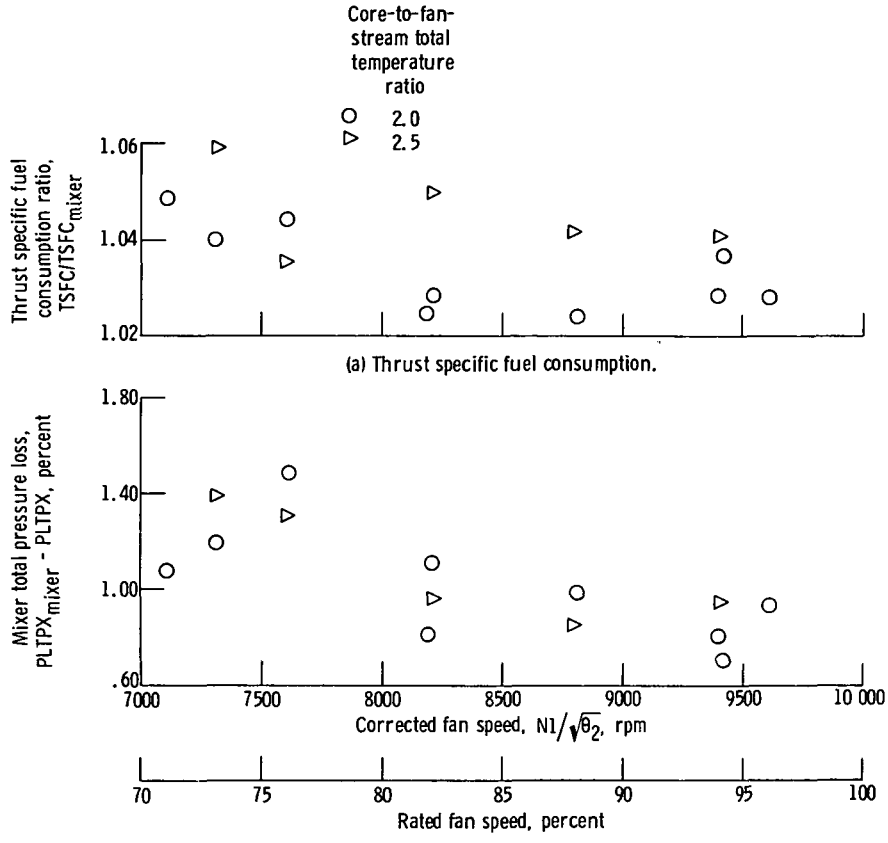



Figure 14. - Mixer performance at two core-to-fan-stream total temperature ratios. Mixing-length-to-diameter ratio, L/D, 0.95; altitude, 12 190 meters (40 000 ft); flight Mach number, 1.4.

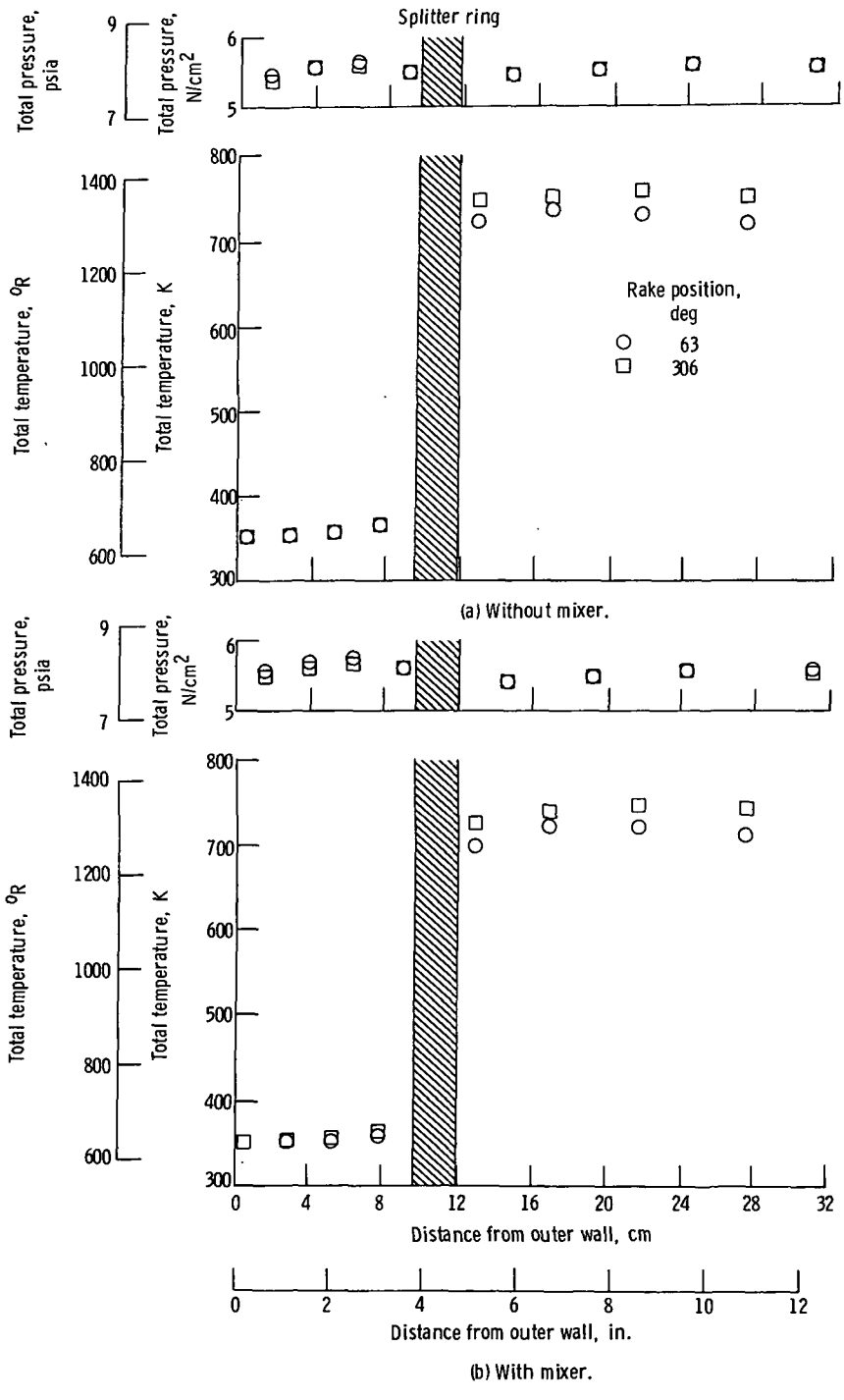



Figure 15. - Temperature and pressure profiles at mixer inlet (station 7.5). Altitude, 10 670 meters (35 000 ft); flight Mach number, 0.8; rated fan speed, 82 percent.

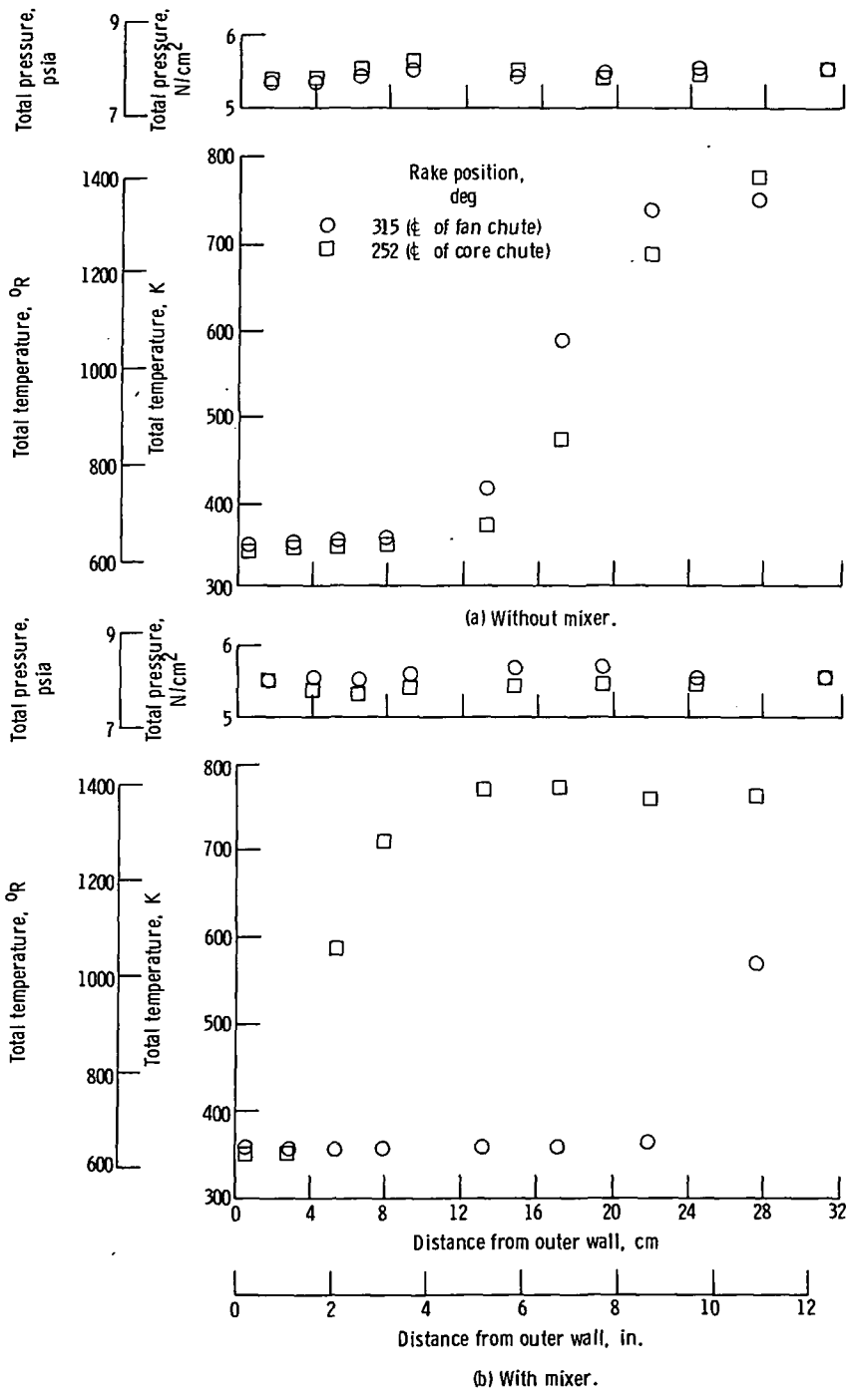
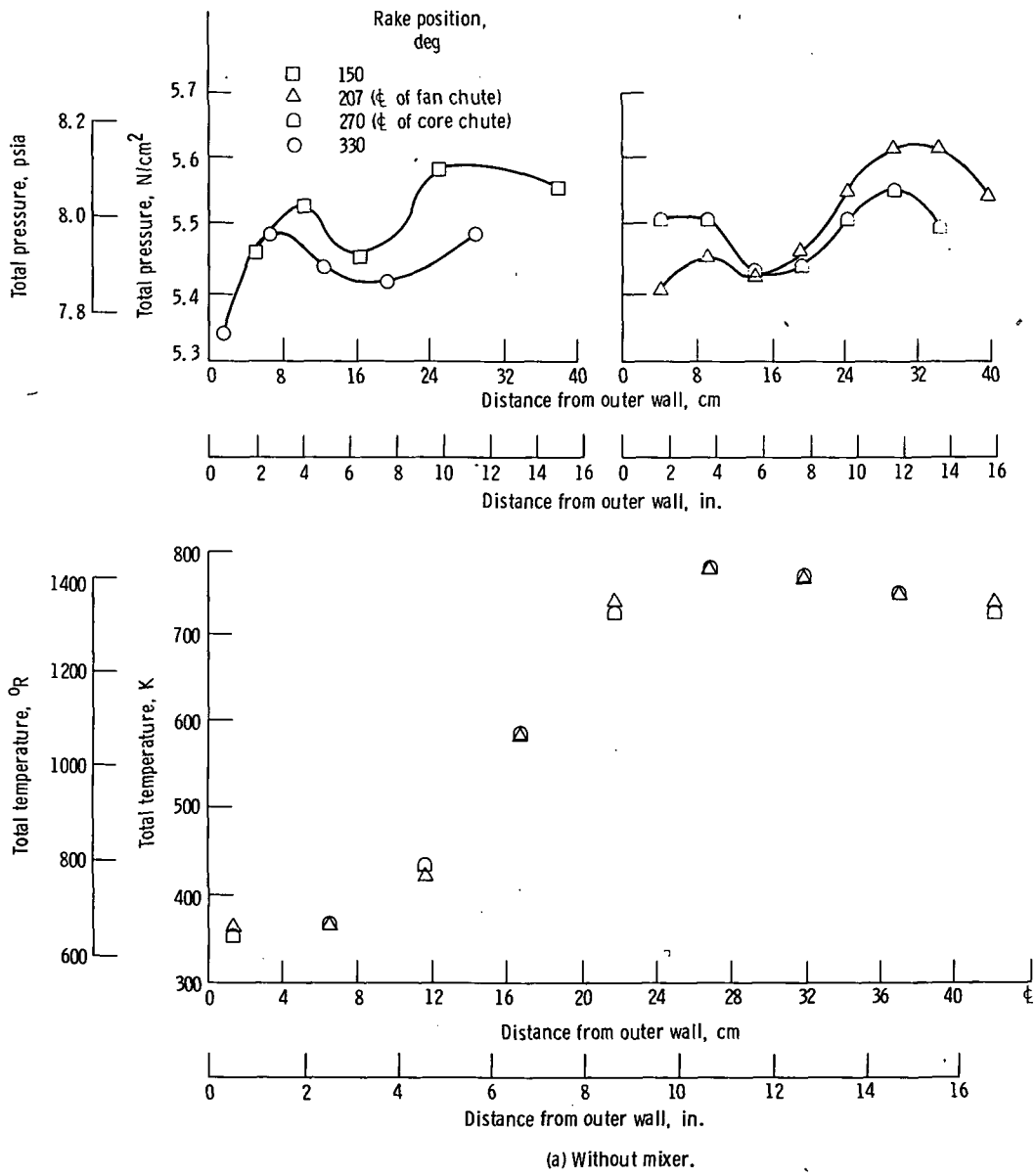
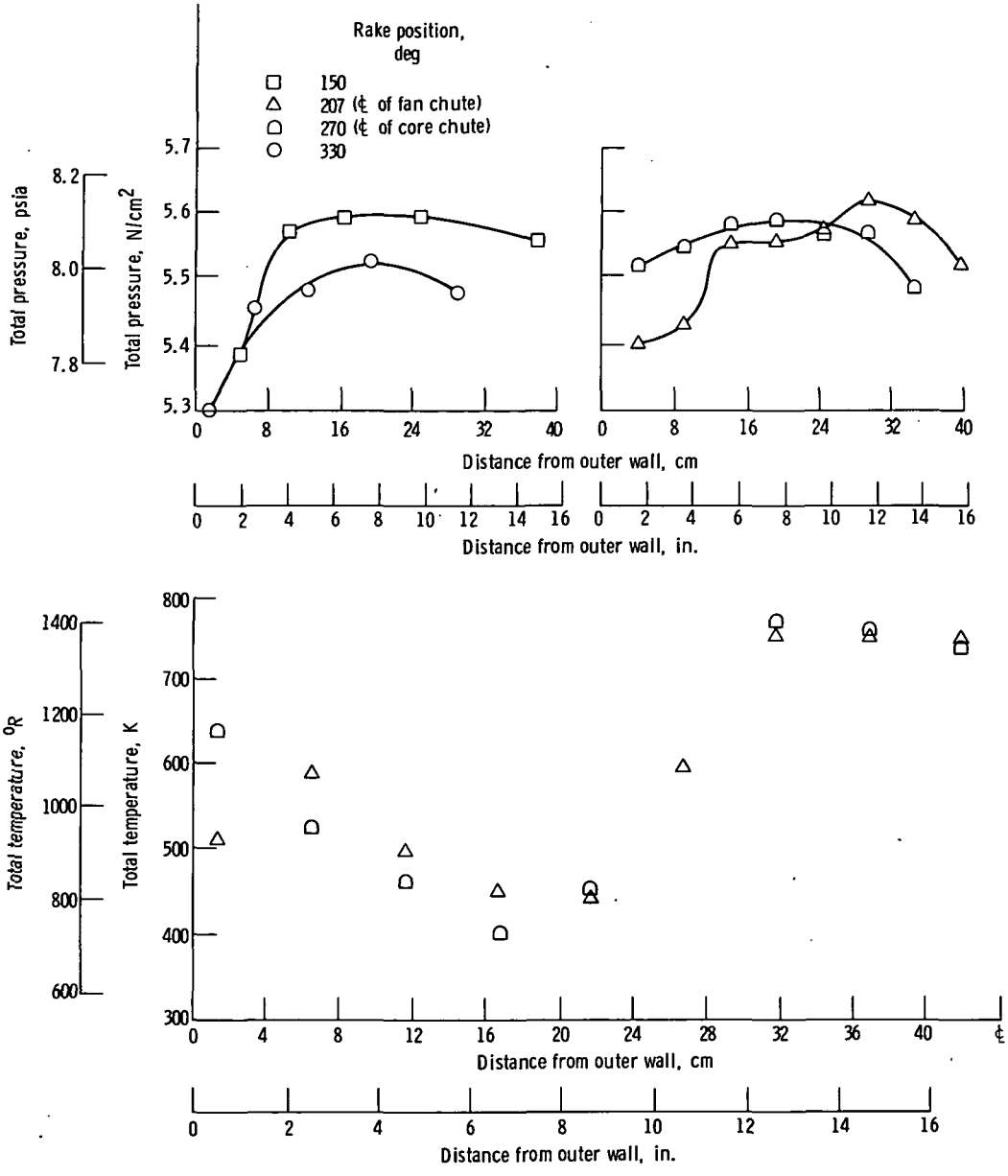



Figure 16. - Temperature and pressure profiles at mixer outlet (station 8). Altitude, 10 670 meters (35 000 ft); flight Mach number, 0.8; rated fan speed, 82 percent.




(a) Without mixer.

Figure 17. - Temperature and pressure profiles at nozzle inlet (station 9). Altitude, 10 670 meters (35 000 ft); flight Mach number, 0.8; rated fan speed, 82 percent.




(b) With mixer.

Figure 17. - Concluded.

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